Finite Element Prediction of Temperature Rise Distribution in Turning Process of AISI 1045 Carbon Steel

Assmaa A. Kawi
Mechanical Engineering Dep.
College of Engineering
University of Basrh

Sana J.Yaseen
Mechanical Engineering Dep.
College of Engineering
University of Basrh

Rana L.
Mechanical Engineering Dep.
College of Engineering
University of Basrh

Abstract

In this paper the code DEFORM-3D V6.1 was used to perform a finite element analysis simulating the turning process of AISI 1045 carbon steel. A series of thermal simulations have been performed, the value and location of maximum temperature have been determined. The comparison of the simulations with earlier works gave promising trend for the presented work with a maximum percentage of error 3.23%. The results of this work show that the maximum temperature exists in the vicinity of the cutting edge. i.e. in the tool-chip contact and then starts cooling immediately when the tool crosses this region. Besides the maximum temperature in the tool-chip interface increases as the cutting time increases until the process reaches the steady-state condition where the temperature is alternating around the mean temperature. Finally the behavior of temperature differs in value and distribution for the same location and time (same boundary conditions) in the cutting direction with the change in depth of cut where the maximum temperature occurs at maximum depth of cut.

تنبؤ نظرية العناصر المحددة بتوزيع ارتفاع درجات الحرارة في عملية الخراطة

المستخلص

في هذا البحث استخدم برنامج Deform-3D V6.1 لإجراء تحليل العناصر المحددة لمحاكاة عملية قطع متعامد لصلب كاربوني نوع AISI 1045. تم تنفيذ سلسلة من عمليات المحاكاة لتحديد قيمة ومكان درجة الحرارة القصوى. تم مقارنة نتائج العمل الحالي مع أبحاث سابقة ولوحظ وجود توافق مقبول بين النتائج حيث كانت أعلى نسبة للخطأ3.23%.نتائج العمل الحالي تؤكد بأن درجة الحرارة القصوى موجود على مقربة من حافة القطع في منطقة تلامس الأداة مع الرايش ثم تبدأ درجة الحرارة بالانخفاض على الفور عندما تتجاوز الأداة هذه المنطقة. بالإضافة إلى ذلك تزاد قيمة درجة الحرارة القصوى في منطقة تلامس الأداة مع الرايش كلما تقدمت الأداة حتى تصل عملية القطع إلى حالة الاستقرار التي تبدأ بعدها درجة الحرارة بالتذبذب حول قيمتها المتوسطة. أخيراً وجد إن سلوك درجة الحرارة يختلف من

حيث القيمة والتوزيع لنفس الموقع والوقت (نفس الشروط الحدية) في اتجاه القطع مع التغيير في عمق قطع حيث لوحظ ان أقصى درجة حرارة تحدث في أقصى عمق قطع.

1. Introduction

During metal cutting, the work of plastic deformation and friction between the cutting tool and workpiece are the main heat sources and can result in a significant temperature increase both in the machine material and the cutting tool. The temperature increase, in its turn, changes material properties such as the yield stress, coefficient of thermal expansion, conductivity and specific heat, thus influencing deformation processes and stresses evolution in the workpiece[1].Generally, increasing temperature decreases the strength of the workpiece material and thus increases its ductility[2] . Besides, analysis of the thermal fields in metal cutting has been the topic of research interest for many years. It is a complex problem, involving many parameters and is too cumbersome to be truly simulated in any mathematical form. The problem zone being too small, any experimental technique would also have definite limitations in practical application and in these cope and reliability of the measurements. Nevertheless, it is undoubted that the thermal phenolmenain metal cutting play a vital role in influencing the tool wear rate. Shear zone temperatures influence the deformation process and in effect the chip–tool interface temperatures[3]. Another added complexity is the characteristic influence of the steep thermal gradients that gives rise to thermal stresses. Furthermore , the combined thermo-mechanical stresses would result in complex stressed states for the cutting tools.

The generation of heat arises from several main sources, namely the primary shear zone at the tool workpiece interface, the secondary shear zone at the tool chip interface, and at the clearance face contact[4].All energy involved in plastic deformation (in the shear zone and at the chip–tool interface) is converted into heat[5].

The temperature in the primary and secondary shear zones are usually very high ,due to the high shear and friction energies dissipated during a machining operation[6].The temperature distribution in the work material and tool-chip is affected by tool material, workpiece material ,cutting speed, feed deep and the tool coating materials. Obviously, it is necessary and significant to establish the nature and distribution of the metal cutting temperatures.

An analyses of the one-dimensional transient temperature distributions in monolayer coated tools and the analytical formulae of the transient temperature distributions for the monolayer cutting tools were obtained using Laplace Transform was presented by[7] .Heat partition and the temperature rise distribution in the moving chip as well as in the stationary tool due to frictional heat source at the chip tool interface alone in metal cutting were determined analytically .This was studied by[8] using functional analysis. A novel approach to the prediction of cutting temperature in multi-layer coated tools was presented. This approach considers the contact mechanics at asperity level and resulting thermal constriction resistance phenomenon [9].Proposition of an innovative approach, based on a simple inverse procedure, in order to identify both the heat flux flowing into the tool through the rake face and the heat transfer coefficient between the tool and the environment during a typical orthogonal cutting process. It is worth pointing out that the effective determination of such quantities is necessary in order to carry out a reliable prediction of the temperature distribution in the tool during the process [10].The tool-chip interface temperature is measured experimentally during turning of EN-31 steel alloy with tungsten carbide inserts using a tool-work thermocouple technique[6]. The relevance of temperature measurement method to high speed cutting. New temperature measurement results obtained by a thermal imaging camera in high speed cutting of high strength alloys are also presented [2].A study deals with the qualification of the tribe logical system ‘work material–coated carbide cutting tool–chip’ to achieve a clearer understanding of the heat flow during the turning process in tool substrates, this highlights the advantages offered by certain coatings which combine hardness and self-lubricating properties, for example (Ti,Al)N+MoS2 [11]

The FEM package applied allows the temperature distribution and heat flux intensity to be predicted closer to appropriate measurements and computations [12].Also, chip formation and possibly its breaking can be determined faster than using costly and time consuming experiments. It is especially important that FEM analysis can help to investigate some thermo dynamical effects occurring in the cutting zone which, as so far, cannot be measured directly [13].A study was done to compare two variants of the FEM simulation model of orthogonal cutting process of AISI 1045 carbon steel with uncoated and multilayer-coated carbide tools i.e. standard and Power Law–Temperature Dependent (PL-TD) options by [12].

To check the applicability of various simulation models to obtain finite element solutions of cutting forces, specific cutting energy and adequate temperatures for a range of coated tool materials and defined cutting conditions commercial explicit finite element code Third wave Advantage has been used in simulations of orthogonal cutting processes performed by means of uncoated carbide and coated tools also studied by [14] using Commercial explicit finite element code Third wave Advantage. Two different approaches were proposed in [15], a former based on a pure thermal simulation once the thermal flow on the tool is properly calculated. The latter, on the contrary, is based on an artificial modification of the heat transfer coefficient at the interface between the chip and the tool in the thermo-mechanical simulation.

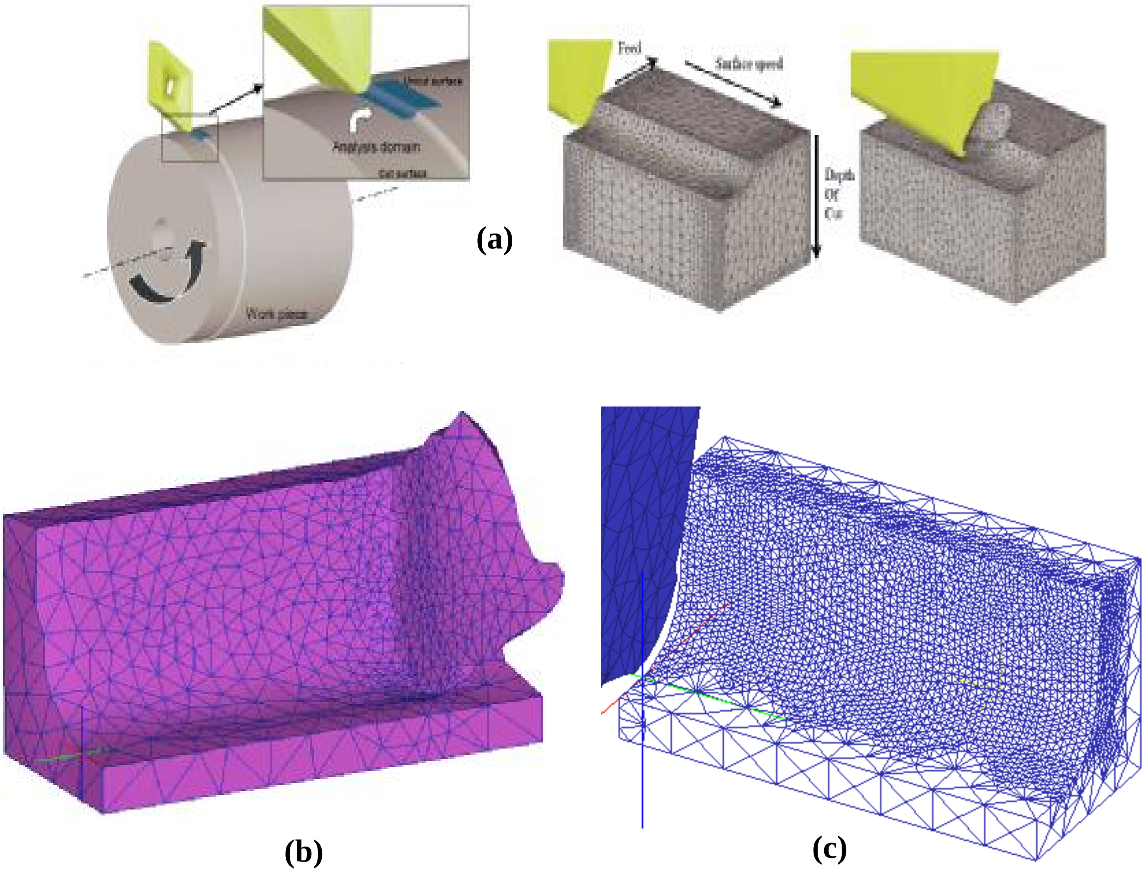
2. Finite element model

2.1. Description of the simulated model

In recent years, the finite element method has particularly become the main tool for simulating metal cutting processes. Finite element models are widely used for calculating the stress, strain, and temperature distributions. In consequence, temperatures in the tool, chip and work piece, and possibly its breaking can be determined faster than using costly and time consuming experiments. It is especially important that FEM analysis can help to investigate some thermo dynamical effects occurring in the cutting zone which, as so far, cannot be measured directly.

In this paper the code DEFORM-3D V6.1 was used to perform a finite element analysis simulating the turning process this finite element model used for the plane-strain orthogonal metal cutting simulation is based on the Lagrangian techniques, thermo-mechanically coupled modeling software with adaptive remeshing.The initial arrangement of both the workpiece and the tool in the simulation model shown in Figure (1-a). In simulations with adaptive remeshing the initial mesh becomes distorted after a certain length of cut as shown in Figure (1- b) and is remeshed in this vicinity to form a regular mesh again. In simulations with DEFORM-3D there is no separation criterion defined and then chip formation is assumed to be due to plastic flow. Therefore, the chip is formed by continuously remeshing the workpiece. The upper part of mesh, which constitutes of the removed workpiece material, is finer, to enable the stress, strain, strain rate and temperature in the chip and the tool tip regime to be accurately predicted. In the present work the mesh style of workpiece taken shown in Figure (1-c) which consists of about 9680 three-nodded plane-strain triangular elements. Dimensions of the element size can range from the minimum value of 0.065mm to maximum one of 0.525 mm**.**

The entire cutting process is simulated, i.e. from the initial to the steady state phase. The workpiece material of choice, AISI 1045 carbon steel, is modeled as thermo elastic-plastic and the friction between the tool and chip is of Coulomb type with the . value of 0.5.The three-dimensional energy equation for the whole cutting domain including workpiece, chip and tool is solved numerically and the model requires the heat generation as an input.



(a)

(b)

(c)

Figure(1).(a) Simulation model of the turning process used .
(b). Shape of the deformed chip after a tool path of 4.01mm .
(c) .Representation of mesh used.

2.2. Heat generation model

As a first approximation, it can be assumed that all of the mechanical energy associated with cutting or chip formation is converted into thermal energy. The heat generation is estimated based on the measured shear stress and shear strain rate relations[16].

Assuming that the work of deformation is the energy converted into thermal energy, the rate of heat generation per unit deformed volume is in primary zone expressed as:

$$\mathring{Q} = \mathcal{T}\,\mathring{\gamma} = \sigma\,\mathring{\varepsilon} \tag{1}$$

where the stress σ and the strain rate $\dot{\varepsilon}$ have to be estimated from the experimental data or relations. τ is the shear stress, $\dot{\gamma}$ is the shear strain rate.

While the heat generation rate per unit volume at any point in the secondary zone is [16].

$$q_s = \tau_s \dot{\gamma}_s \tag{2}$$

2.3. Heat Transfer

The heat generated in the shear zones and at the rake face is dissipated in the chips and workpiece by conduction and lost to the ambient by convection. The governing equation for three-dimensional transient heat conduction is given as [17]

$$\frac{\partial^2 T}{x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{q}{K} = \frac{1}{\alpha}\frac{\partial^2 T}{\partial t^2} \tag{3}$$

which is subject to the following boundary conditions:

$$-k\frac{\partial T}{\partial n} = hc(T - T\infty) \tag{4}$$

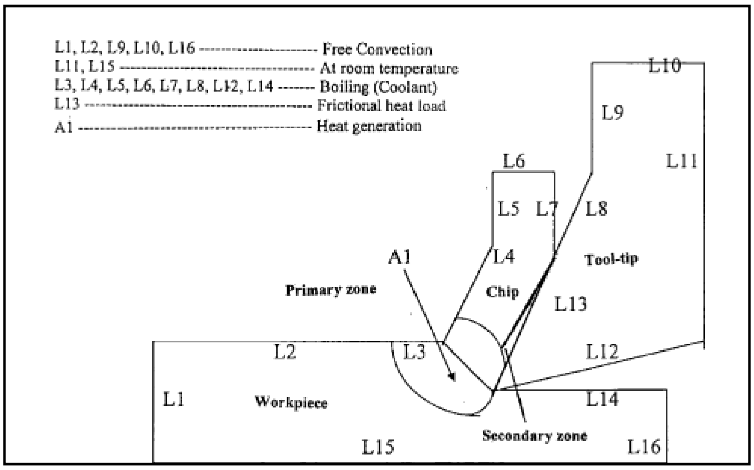
Where T,q and t are temperature, heat generation per unit volume and time respectively. T_∞ ambient temperature which taken equal to 20°C, κ ,α are the thermal conductivity and the thermal diffusivity values for the workpiece, respectively, and h_c convection film coefficients for the different surfaces have been arrived at by using the standard correlations for free convection and boiling for horizontal, vertical and inclined surfaces. Figure (2)shows the heat generation and different convective conditions used on different surfaces of the model.

2.4. Cutting conditions

The tool geometry and the cutting conditions used for the orthogonal metal cutting simulation are presented in Table (1), based on the data used by[18].

Table (1) . Cutting conditions and tool geometry.

Tool rake angle = -5°	Depth of cut = 0. 5, 1, 1.5, 2, 3 mm
Tool clearance angle = 5°	Cutting speed = 103.2 m/min
Undeformed chip thickness = 0.16 mm	Coulomb friction coefficient = 0.5



Figure(2). Heat source and boundary conditions for the model [16].

3. Results and discussion

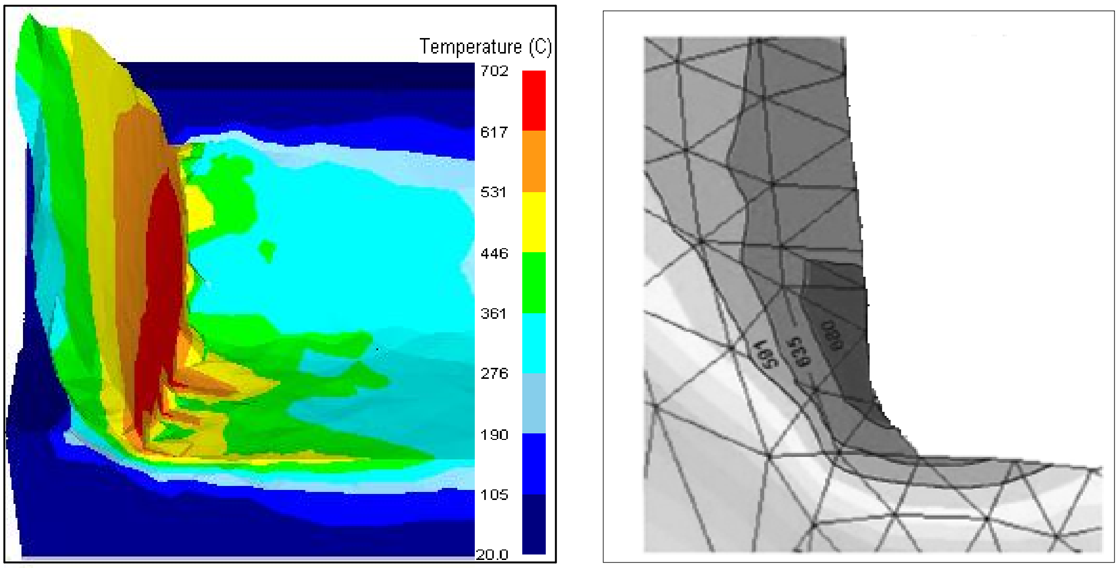
3.1 Verification of the constructed model

To validate the predicted results obtained from the present constructed finite element model, it is necessary to compare these results with those of other authors.

3.1.1 Case 1:Dscribes temperature distribution in the cutting zone

This validation case shows the temperature distribution in the cutting zone i.e the tool-chip interface, were carried out for constant cutting parameters, i.e. cutting speed of 103.2 m/min, feed rate of 0.16 mm/rev and depth of cut of 2 mm. All cutting conditions, including tool's geometrical features, listed in Table (1)were chosen based on the data used in Ref.[18].

The temperature distribution in the workpiece and chip after a tool path of 4.0 mm, is shown in Figure (3). The temperature distribution predicted by present work with a maximum temperature of 702 °C at the tool-chip interface, is shown in Figure (3-a), while Figure (3-b) shows the simulated results predicted by Reference[18] with a maximum temperature of 680 °C,(error 3.23%) which means there is good agreement between the two results.



(a) (b)

Figure (3). Comparison between computed values of the interface temperature and reference [18].

3.1.2 case 2: Temperature distribution versus simulation Time

Figure(4) shows the relationship between maximum temperature in the tool-chip interface with time predicted by present work compared with numerical results predicted by Ref.[14] using same conditions given in ref.[14]. The comparison shows that there is good agreement with maximum percentage error of 2.06% in the mean temperature after reaching steady state.

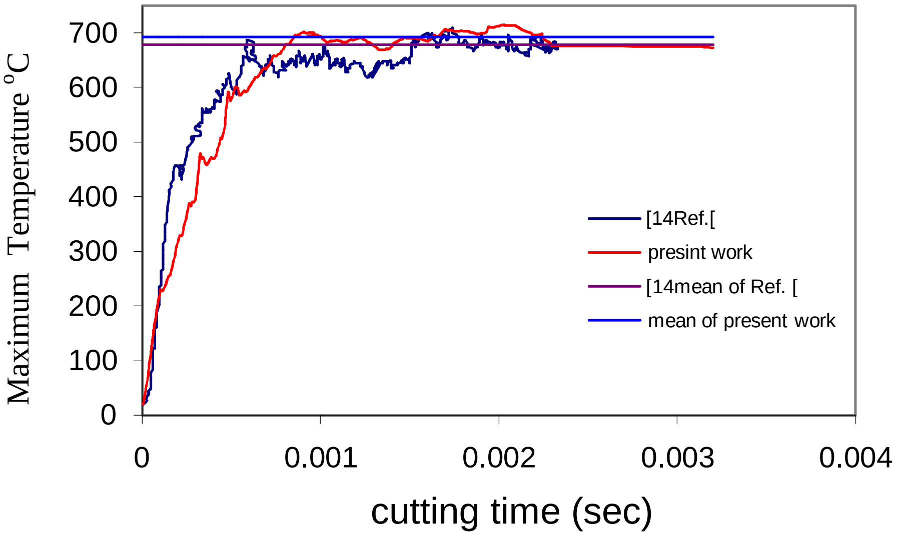


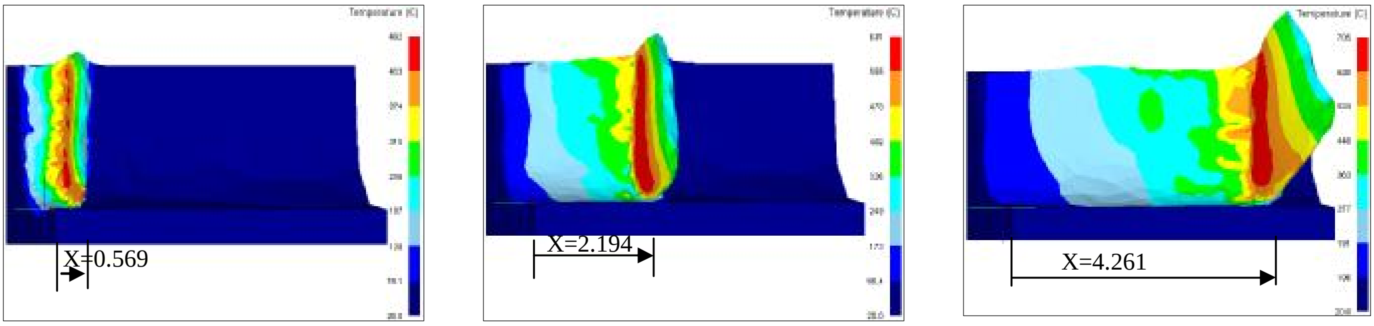
Figure (4). Average interface temperature trace vs. simulation time.

3.2 Temperature distribution

The results obtained from the application of cutting conditions involved in this work refers to the temperature distribution which depends on the depth of cut, cutting time and the position of the nod from the chip. These results can be arranged in the following manner:

3.2.1 Temperature behavior versus time

From the comparison among Figure (5a, b and c) for a depth of cut 2mm, we can be observed that more heat is transferred to the chip and workpiece and areas with the maximum temperatures are localized near the tool-chip interface. In consequence, the maximum interface temperature exists in the vicinity of the cutting edge. i.e. in the first part of the tool-chip contact and then start cooling immediately when the tool across this region. So to study this behavior, different nodes were taken in different position as show in Figure(6), where these nods coordinates are A (-0.917,0.133 ,0.990), B (-0.959 ,1.310 ,0.990), C (-0.970,2.450,1.030) and D(-0.962, 4.5,1.020).



(a) (b) (c)

Figure(5). Temperature behavior with cutting tool progress(a) cutting time 39E-5sec. (b) cutting time 12E-4sec .(c) cutting time 24E-4sec .

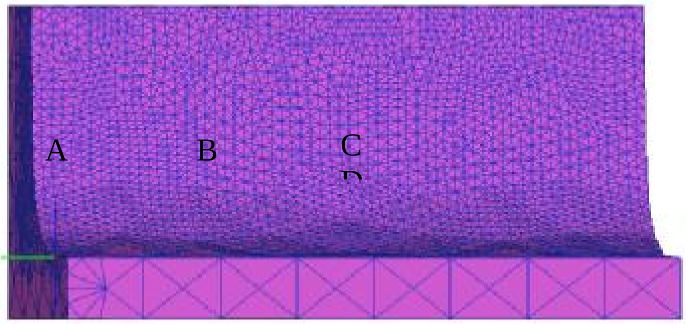


Figure (6). Node position on the work piece.

The temperature variation in these nodes with time during cutting process was illustrated in Figure(7) .It is clear that all nodes obey the same behavior although the maximum temperature at each one not equal. The temperature at node D reach a maximum value 621.4 ˚C compared with nodes A, B and C. This can be concluded to the heat transfer by conduction through the workpiece at node D, which is accumulated from the other nodes. Figure (8) shows that there are raising in temperatures in the region ahead the chip on the workpiece due to conduction.

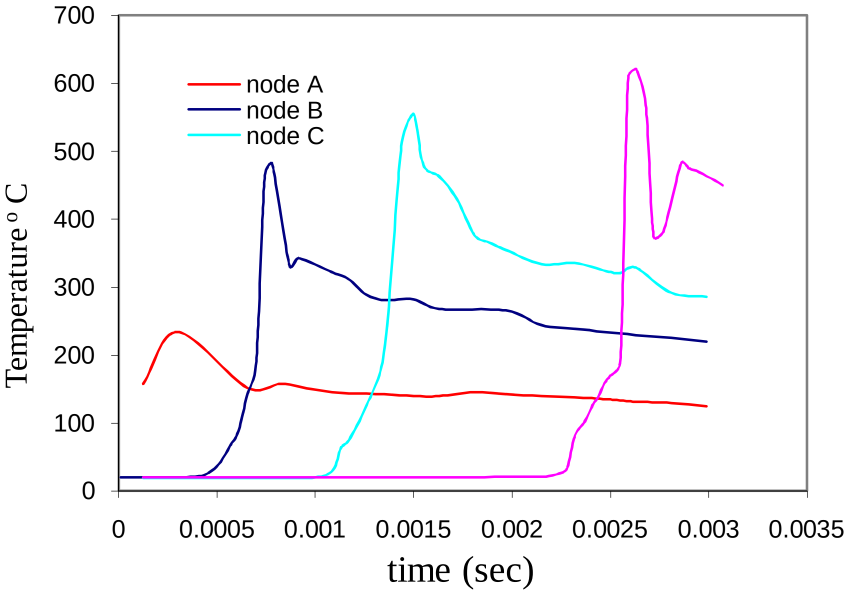
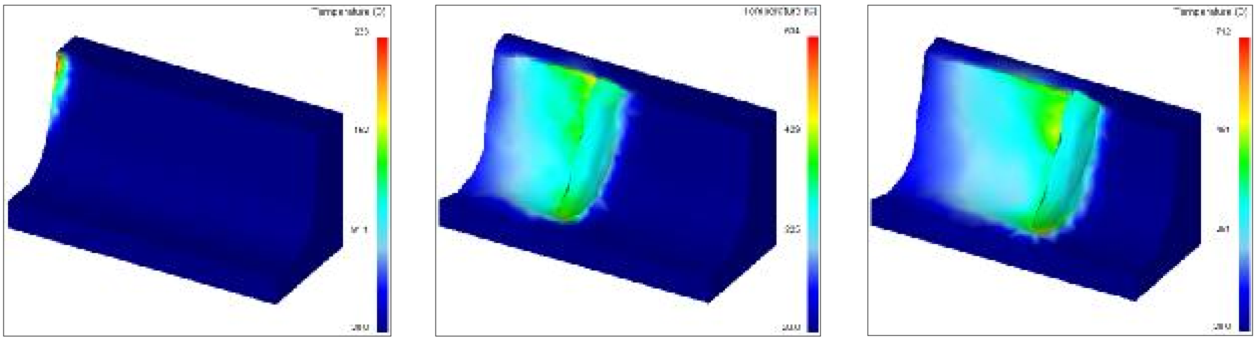


Figure (7) . Temperature distribution with time for different location.

Also the difference in the value of temperature increase among the nodes A, B,C, and D is not constant and reduce with time until reach an alternating range. This result agree with the result shown in Figure (9).



(a) **(b)** **(c)**

Figure (8). Regions of rising tempertures before reach cut to them.

3.3. Cutting temperature

3.2.2 Cutting temperature

The appropriate temperature histories obtained during simulations along with corresponding values of the maximum workpiece temperatures are shown in Figure (9). It was established based on temperature traces with tool travel that the time required to reach the steady-state temperature was approximately 0.65ms. As can be seen from these records, the value of mean temperature are reach to close values (reach steady state) and this explains why the temperature dose not continue to raise.

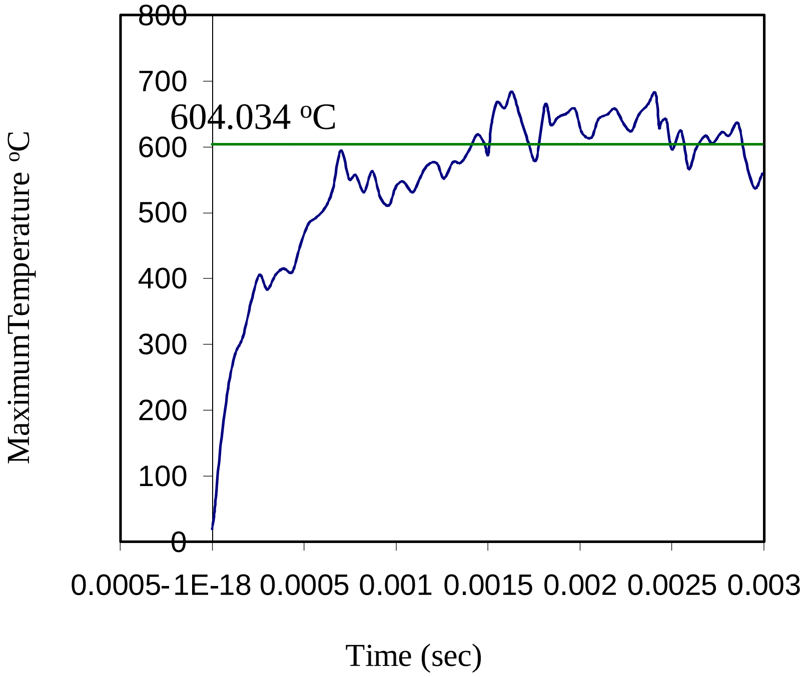
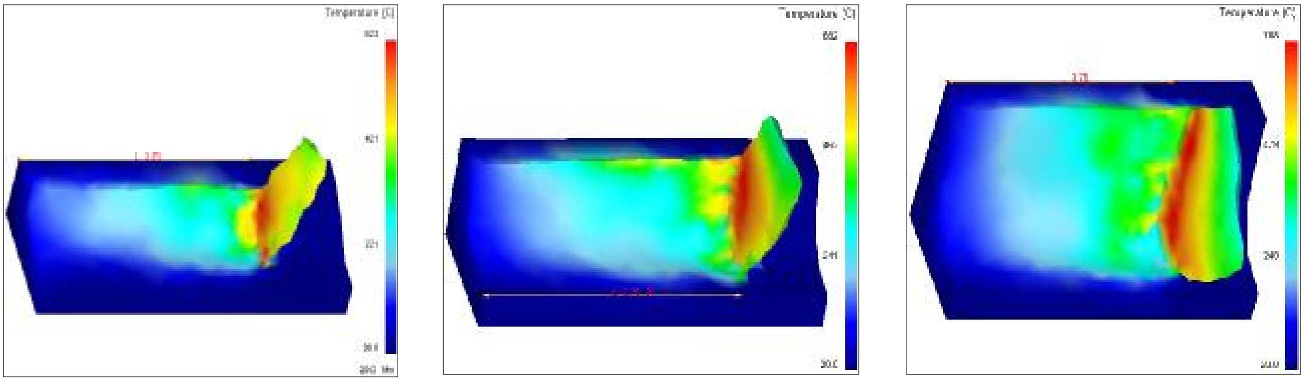


Figure (9) . Relation between maximum temperature and time.

3.3 Temperature variation with depth of cut

Behaviour of temperature differs from the value and the distribution form for the same location and time (same boundary conditions) in the cutting direction with the depth of cut, the maximum temperature for depth of cut 0.5mm reaching a 622˚C while its reaching 708˚C for depth of cut 2mm. As the depth of cut increase the area with high temperature increases, see Figure (10), and the rise of temperature not limited in cutting zone only, but contain the vicinity regions for the cutting depth (at the top of workpiece) that’s belongs to heat conducting which the temperature rise from 221°C to 249°C at depths 0.5mm and 2mm respectively.



(a) (b) (c)

Figure(10). Temperature behaviour with different depth of cut. (a) t1=0.5mm, (b) t1=1mm, (c) t1=2mm (c)t1=2mm.

Temperature hysterias obtained during simulations along with corresponding values of the average workpiece temperature for different depth are shown in Figure (11). Based on temperature traces with tool travel that the time required to reach the steady-state temperature was depending on the depth of cut . For 0.5 mm reach to steady faster than other depth approximately at time0.228ms while it was 0.564 and 0.65msec for 1mm and 2mm respectively . As can be seen from these records, the value of mean temperature are reach to close values (reach steady state) in a time has an inverses relation with depth of cut. Figure (12) shows temperature course for same nod has a position of (-0.96, 2.51,0.95) with time for different depth of cut ,this figure insure the relation between temperature and depth of cut. That temperature increasing with increase depth of cut , this belong to increase the cutting force cutting (cutting work) to overcome the friction ,since with increasing depth of cut means cutting more amount of the cutting metal and all this work convert to heat.

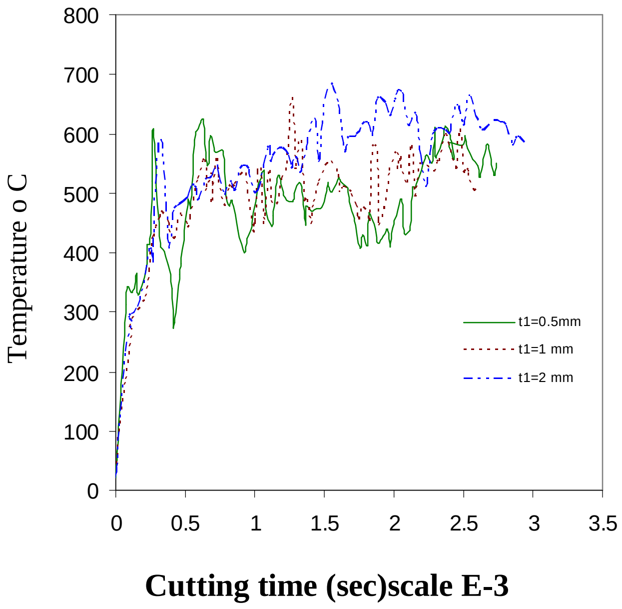


Figure (11). Interface temperature trace vs. cutting time for different depth.

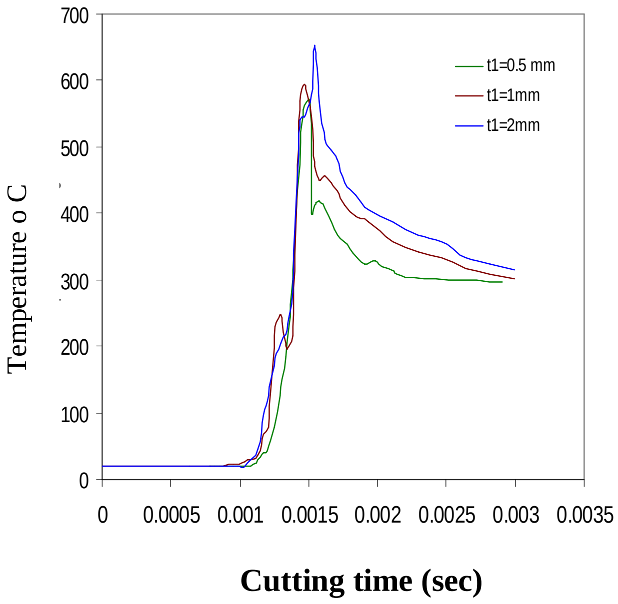
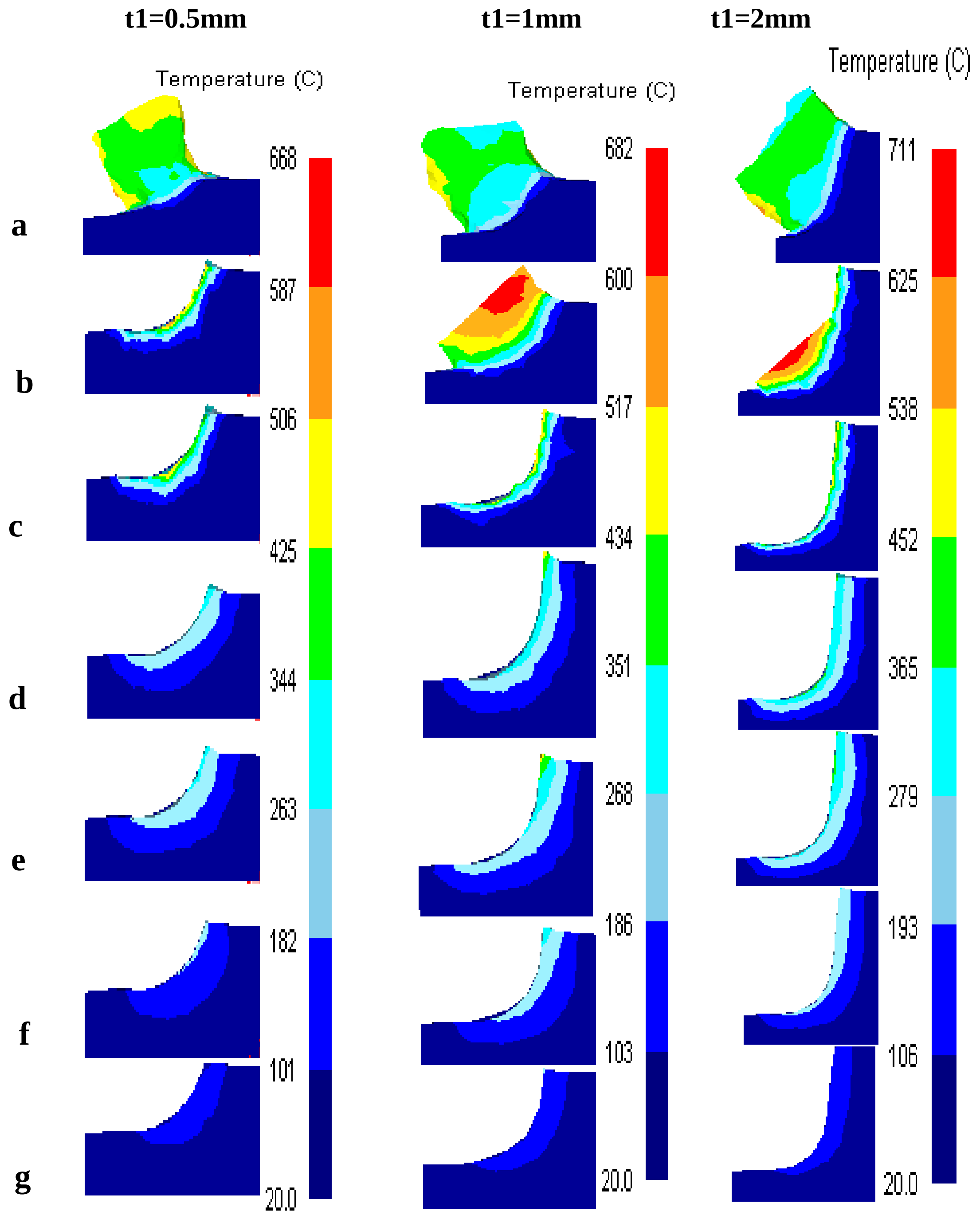


Figure (12) . Temperature vs. time at different depth of cut for the same position.

Temperature distribution in a direction perpendicular to the cutting direction at different depth of cut and 4mm distance from the cutting edge was illustrated in Figure (13). The region ahead the cutting edge which represented in Figure (13- a), it can be noticed that region is small at depth t1=0.5mm and increase with increasing the depth of cut, this mean that the region which expose to heat transfer by conduction increase with the depth of cut. The cooled region areas reduce with increase the depth of cut see Figure (13-b). Also the results show that the regions with high temperature in all depths appears at distance 0.1 to 0.25 mm from the cutting edge .While regions of high temperature (340 to 450) disappear only for depth 0.5mm after 1mm from the cutting edge. The fast reduction in temperature leads to increase the area of low temperature region (101 to 182)° C for depth 0.5, and (103-186)°C for depth of cut 1mm as shown in Figure(13- f) and Figure (13- g) .



Figure(13). Magnification of temperature distribution on the depth of workpiece after a tool path of 4.0mm for t1=0.5mm ,t1=1mm ,t1=2mm and different positions a)4.3mm b)3.93mm c)3.75mm d)3mm e)2.5mm f)1.5mm g)0.57mm from starting cutting.

4. Conclusions

The aim of this finite element modeling was creating a FEM simulation model in order to obtain and research: numerical solutions of cutting forces, temperature in the contact region and workpiece material and plastic strain during turning the steel.

The following conclusions may be drawn from the results of this work:

1. The results obtained from the present work verify that the cutting process could be numerically estimated using the finite element method with a reasonable degree of accuracy.
2. The maximum temperature exists in the vicinity of the cutting edge. i.e. in the workpiece then start cooling immediately when the tool across this region.
3. The maximum temperature in the workpiece increases as the cutting time increase until process reach the steady-state condition where the temperature alternating around the mean temperature.
4. Behaviour of temperature differs in value and distribution for the same location and time (same boundary conditions) in the cutting direction with the change in depth of cut. The maximum temperature occurs at maximum depth of cut certainly this belong to increase the cutting force (cutting work) to overcome the friction.
5. The temperature for all nodes obey the same behaviour through cutting processes, although the maximum temperature (when the tool reach to theses nods) at each one not equal.
6. Temperature histories obtained during simulations along with corresponding values of the maximum workpiece temperature for different depth. based on temperature traces with tool travel that the time required to reach the steady-state temperature was depending on the depth of cut, as well as the value of mean temperature are reach to close values (reach steady state) in a time has an inverses relation with depth of cut.
7. Temperature distribution inside workpiece (perpendicular on the cutting direction) at different depth of cut represent by regions(which previous the cutting , region which expose to heat transfer by conduction) which limited at depth t_1=0.5mm and increase with increasing the depth of cut.
8. It can also be important for practice that the maximum interface temperatures predicted can support the choice of depth of cut for defined machining parameters in order to avoid excessive thermal loading on the workpiece.

5.Acknowledgements

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